

Performance of flammability of kerosene and NO_x emission in the porous burner

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The present study aims to develop the porous ceramic burner applicable to the Stirling engine, boilers and gas turbines using liquid fuels with the flammability in a large input load. As a liquid fuel, kerosene is supplied dropwise on the top surface of the porous ceramic plate and ignited on the bottom surface. The combustion behavior of the burner is examined by measuring the profiles of temperature and composition of combustion gas along the centerline in the chamber. The promotion effect of combustion is examined experimentally by installing a wire net at the chamber outlet. The boundary condition of the combustion changes substantially in the presence of the wire net. The behavior of NO_x formation can be correlated by a function of the equilibrium NO concentration at a maximum temperature in the burner. © 1998 Elsevier Science Ltd.

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INTRODUCTION

Combustion of liquid fuels is commonly conducted using a spray burner for industrial applications such as furnaces and boilers. The stability of the flame of the spray burner is significantly influenced by the aerodynamic behavior of air and fuel droplets. Many investigations on liquid fuel combustion placed the emphasis on the size, the concentration and the motion of droplets sprayed through a nozzle^{1–8} as well as NO_x and/or soot emissions^{9–12} and flame structures^{13–15}. However, little work has been carried out on the technical problem of expanding the flammability regions. From the viewpoint of energy utilization, burners which make stable continuous combustion possible in a wide range of heat load for liquid fuels are required. If such burners are available which produce low NO_x emissions, they will be used in various applications involving a Stirling engine that requires an extremely large turn-down ratio of about 5–10. For the development of those burners, improvement of the flame stability is essential. However, it does not appear as straightforward to achieve the performance in the spray burner which matches that of gaseous fuels. Alternatively, the combustion of fuel vapor–air systems may be one candidate of burners which are able to produce such a performance. It is considered that the control of liquid fuel vaporization and the mixing of the vapor and air are important factors in the system. Nevertheless, there has been little attempt to develop those burners without using an auxiliary heater for fuel vaporization.

In the present study, the porous ceramic burner is applied to the combustion of liquid fuels. Itaya *et al.*¹⁶ and Nakamura *et al.*¹⁷ reported obtaining a steady flame when burning a methane–air mixture in an open atmosphere on a porous ceramic plate which functions as a flame holder. Itaya *et al.*¹⁸ later studied the surface combustion characteristics of a methane–air mixture on a porous ceramic plate in a cylindrical furnace, and reported that the fuel-lean limit of the methane–air flame not only expanded, but also the surface temperature of the ceramic plate rose owing to the added effect of thermal radiation from the furnace wall, compared with the case of the open atmosphere. The behavior of methanol vaporization and reformation in a porous ceramic irradiated by thermal radiation was studied by Hanamura *et al.*¹⁹ Zhang *et al.*²⁰ reported that externally applied radiation influenced the flame structure of a pool fire and/or the vaporization. If the porous ceramic burner is appropriately designed, therefore, the flammability limit against the input load of liquid fuels will be extended by the contribution of the porous ceramic to the effects as a fuel distributor, a fuel evaporator and a flame holder and to the absorption of imposed radiation. In this work, the behavior of kerosene combustion and NO_x emission in the test burner are studied to develop the porous ceramic burner where liquid fuels are burned in the turn-down ratio over 5 while keeping NO_x emissions low.

EXPERIMENTAL APPARATUS AND PROCEDURE

The schematic drawing of the experimental apparatus used for the determination of the combustion characteristics in

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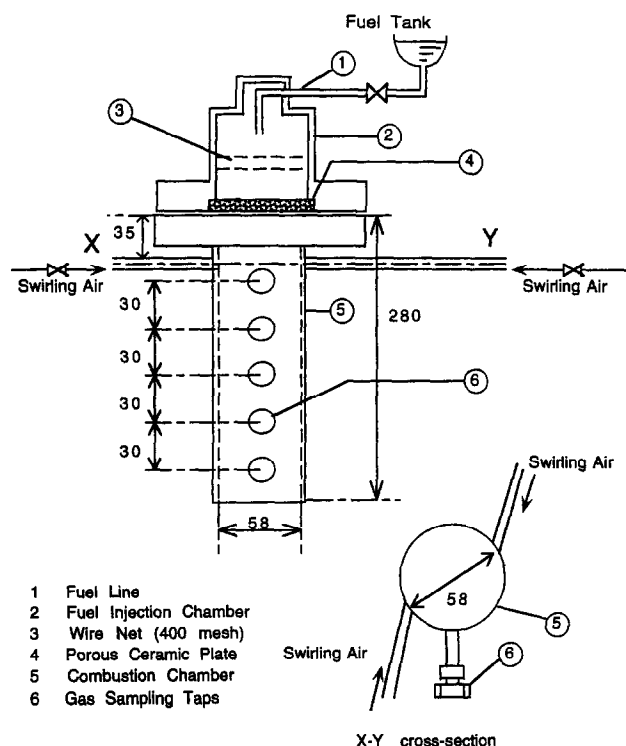


Figure 1 Experimental apparatus

the present study is shown in Figure 1. The burner consists of fuel injection chamber, combustion chamber and a porous ceramic plate. The chambers are based on stainless steel tubes 55 mm i.d. and 120 mm long for the fuel injection section and 280 mm long for the combustion section. The porous ceramic plate 58 mm diameter and 5 mm thick is adjusted to the bottom of the injection chamber. The ceramics is made of mullite with a porosity value of 0.36 and a mean pore diameter of 180 μm . Both chambers are connected so as to sandwich the ceramics. Kerosene as a liquid fuel is supplied dropwise on the top surface of the ceramic plate at a certain flow rate through the oil flow control valve by a pump from a fuel tank. Two pieces of wire net 400 mesh are installed between the fuel injector and the ceramic plate to distribute fuel droplets over the surface as uniformly as possible. The fuel is ignited under the bottom side of the ceramics. The primary air is supplied so as to swirl through two tubes (4 mm i.d.) joined tangentially to the cylindrical wall of the combustion chamber, as seen in the outline of an X-Y cross-section. The air supply is located 35 mm away from the bottom surface of the ceramics. A compressor is employed to avoid the fluctuation of air stream supplied to the chamber. The taps 10 mm i.d. for gas sampling are installed at five positions of 50, 80, 110, 140 and 170 mm in height to the downward direction from the bottom of the ceramic plate. The holes of 1 mm diameter are made on the wall for the temperature measurement at the same heights as the sampling taps.

The combustion characteristics are determined from the profiles of temperature and composition of the combustion gas along the centerline in the combustion chamber. The temperatures are measured by setting horizontally Pt-Pt/13% Rh thermocouples (0.1 mm diameter) to the centerline through the holes on the chamber wall. The water cooling type of the suction probe which consists of a quartz double tube (10 mm o.d.) is used for the gas sampling. The suction probe is placed into the center of the chamber from the

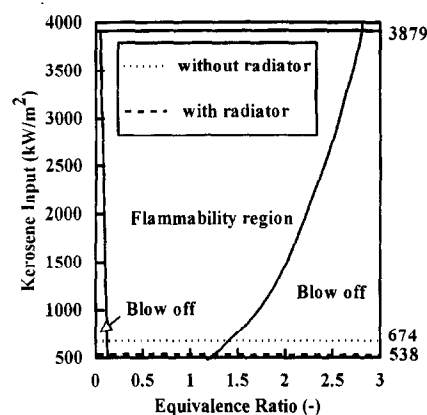


Figure 2 Flammability region

sampling taps, and the gas is led to a reservoir through the probe. The components in the sampling gas are analyzed using gas chromatography with a TCD detector. The concentration of nitrogen oxide is determined using a chemiluminescent NO_x analyzer (Yanagimoto, BCN-611AS). Similar experiments are carried out for the case where a radiator made of stainless steel wire net (20 mesh) is installed at the bottom of the combustion chamber to study the effect of the difference of the boundary condition at the chamber outlet on the combustion behavior. Experimental runs are conducted in the following step: after ignition in the combustion chamber, the flow rates of kerosene and air are adjusted under appropriate conditions. When combustion in the burner attains a continuously stable state, the measurements described above are performed.

RESULTS AND DISCUSSION

Flammability limit

Information on the flammability region is of primary importance in a newly developed burner. The flammability limit in the present burner is plotted on a graph of kerosene input against equivalence ratio in Figure 2. The figure shows both the fuel-lean and fuel-rich limits of the combustion, although the lean limit is rather significant for standard industrial applications. The kerosene input load is defined as the magnitude per unit ceramic surface area, and the load will be used representatively in the following. The flammability limit is defined here by the equivalence ratio where a flame is just extinguished when the rate of air supply rises gradually for a flame burning with each kerosene flow rate. Hence it should be noted that the flammability region is not always a flame stability area, but involves the state of flames existing unstably with fluctuations in the chamber. This burner is flammable even at the extremely low flow rate of kerosene since the flame is considered to be classified as similar to a pool fire. It can be seen that the fuel-lean limit of kerosene-air combustion achieves a low equivalence ratio as low as 0.1. A similar trend was reported for methane-air combustion¹⁸. Although the experiment could not be continued beyond the kerosene input of 3879 kW m⁻² because of the limitation of the air supply capacity with an available compressor, this burner was still flammable at the higher load. The apparent stability of flame is favorable at the input load of 674–3879 kW m⁻² as shown by dotted lines in the figure. Hence the turn-down ratio achieves a value over 5.8. From these results it is established that the present burner has flammability over a

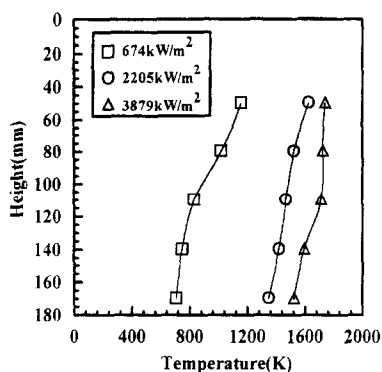


Figure 3 Effect of kerosene input on temperature profile, $q = 0.9$

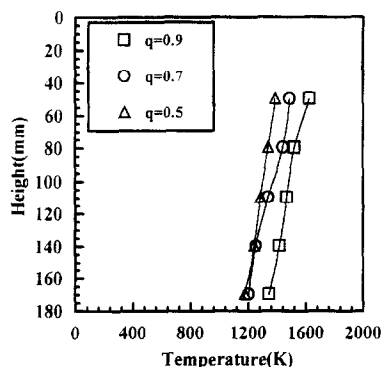


Figure 4 Effect of equivalence ratio on temperature profile, kerosene input: 2205 kW m^{-2}

remarkably wide fuel load and equivalence ratio. This specific feature may be due to the contribution of appropriate kerosene vaporization from the porous ceramics. Once liquid fuels vaporize, the combustion of the vapor–air system takes place using a similar mechanism to that of gaseous fuels. Consequently, the characteristic of the ceramic burner for methane–air, i.e. the effect to prevent the blow-off and flush-back of flames¹⁶, also appeared for kerosene.

Temperature profiles

The flame stability and the completion of combustion are important features required for the evaluation of the burner's performance. The features of this burner was studied in detail. The temperature was measured along the centerline in the combustion chamber in all runs carried out in the experiment at first. *Figure 3* shows example of the temperature profiles of combustion gas. The results are compared at a constant equivalence ratio of 0.9. The ordinate is kept positive downward on the basis of the bottom surface of the ceramics. The temperature fell when the kerosene input became lower as there was no specified insulation on the burner. The feature of the temperature profiles shows a significant difference in the gradient against the height. It implies that the higher load allows the flame length to expand and/or the flame zone to shift downstream. This is because the flame structure is related to the fuel input or the gas flow rate; that is, the slower gas flow rate results in the quick completion of combustion. *Figure 4* shows the effect of equivalence ratio on the temperature profiles with a constant input of 2205 kW m^{-2} . The trend that the flame was lengthened and/or shifted to the downstream appeared

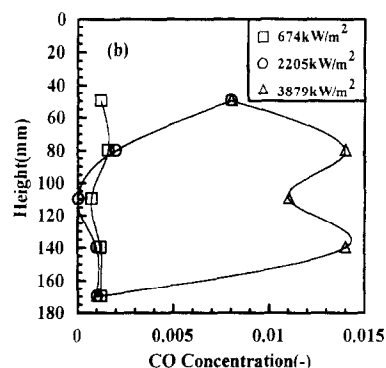
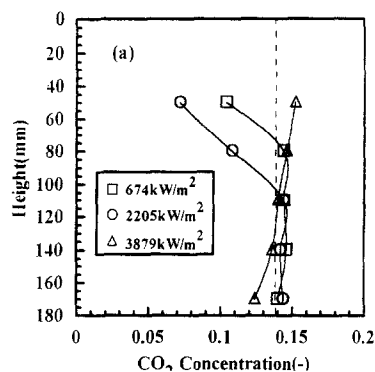


Figure 5 Effect of kerosene input on CO_2 and CO concentration, $q = 0.9$

with a decreasing equivalence ratio from a comparison of the gradients. This behavior can be explained by the fact that the combustion velocity gradually becomes slow when the equivalence ratio decreases.

From these figures, it can be seen that the temperature profiles of the kerosene–air flame are similar to that of the methane–air flame, with the highest temperature located close to the surface of the ceramic plate. However, the position shifts slightly downstream owing to the vaporization of kerosene at the surface of the ceramic plate.

Composition profiles

Figure 5(a) and *(b)* shows the dependency of fuel input on the profiles of CO_2 and CO concentration in the combustion gas (excluding water vapor) in a constant equivalence ratio of 0.9. These results were obtained from the analyses of gases sampled in the centerline of the chamber, and they do not always reflect the concentration averaged over the cross-section due to aerodynamic recirculations by turbulent flame. Therefore, an irregular configuration of the curves was observed in the compositions along the stream, particularly in the CO concentration for 3879 kW m^{-2} . Although a significant amount of CO yielded in the flame zone, the concentration was reduced finally to less than 0.1% and the combustion achieved was almost complete by the height of 170 mm for any kerosene input. The flame length and position predicted from both profiles of CO and CO_2 corresponded well to the behavior of the temperature profiles described above. The yield of CO as an intermediate in the flame zone became remarkable with an increase in the input load due to the temperature rise. In *Figure 5(a)* the stoichiometric concentration of CO_2 estimated is shown by a broken line, and it agreed well with the measured data in the downstream from complete combustion. Hence a carbon

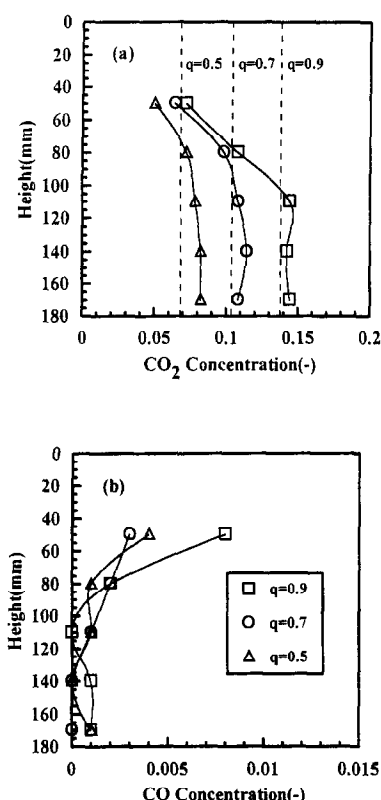


Figure 6 Effect of equivalence ratio on CO_2 and CO concentration, kerosene input: 2205 kW m^{-2}

balance was maintained in those runs. The effect of equivalence ratio on the concentration of CO_2 and CO is shown for a constant kerosene input of 2205 kW m^{-2} in Figure 6(a) and (b). This figure indicates almost complete combustion in equivalence ratios from 0.5 to 0.9. This fact implies that the stable complete combustion in the present burner readily occurs under wide conditions. Good agreement between CO_2 concentration in the downstream and the broken line that represents the stoichiometric value for the corresponding equivalence ratio was observed. Such desirable behavior may be described by the significantly functional mechanism of the porous ceramic plate as the evaporator of kerosene and the flame holder. Additionally, the ceramics can efficiently absorb the recirculation heat by radiation from the flame body and the chamber wall at high temperature. The effect allows the vaporization of kerosene to be properly enhanced.

Effect of radiator at the chamber outlet

The broken line in Figure 2 shows the flame stability limit in the presence of the radiator. The flame stability limit in lean kerosene input is found to be 538 kW m^{-2} . It implies that the radiator allows the stable flammable region to expand into the low kerosene input. Hence the stability of flames is favorable in all runs carried out in the kerosene input load of $538\text{--}3879 \text{ kW m}^{-2}$, and the turn-down ratio achieves over 7.2.

Figure 7 shows the effect of the radiator on the temperature profiles with a kerosene input of 1500 kW m^{-2} in an equivalence ratio of 0.7. The existence of the radiator significantly increases the temperature near the chamber outlet. From this finding it is suggested that the combustion gas temperature is maintained by radiation emitted toward

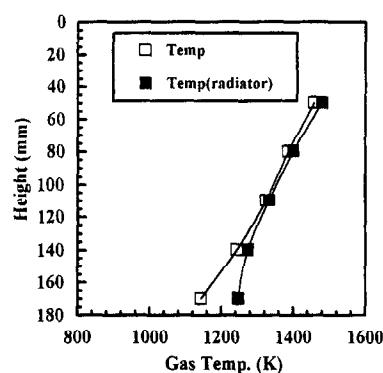


Figure 7 Effect of radiator on temperature profile, kerosene input: 1500 kW m^{-2} ; $q = 0.7$

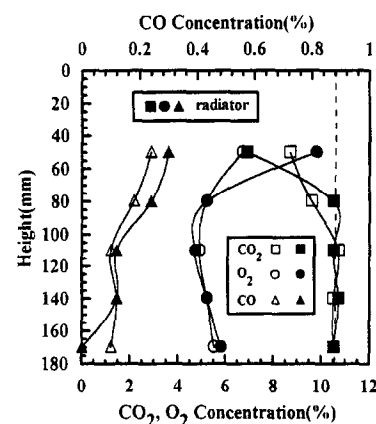


Figure 8 Effect of radiator on CO_2 , O_2 and CO concentration, kerosene input: 1500 kW m^{-2} ; $q = 0.7$

upstream from the radiator. The specific feature of the expansion of the stable combustion area by the radiator installation may be due to the contribution of appropriate kerosene vaporization from the porous ceramics, thus maintaining a higher temperature.

Figure 8 shows the effect of the radiator on the profiles of CO_2 , O_2 and CO in the combustion chamber. The broken line in this figure represents the stoichiometric concentration of CO_2 estimated for the corresponding equivalence ratio and fuel load. The CO concentration at the height 170 mm is found to be almost 0 and 0.1% in the presence and absence of the radiator, respectively. Hence it is noticed that the combustion state is improved by the installation of the radiator at the chamber outlet.

NO_x emission behavior

The reduction of NO_x is an important topic from an environmental viewpoint, even though the performance of other burners is improved. The behavior of NO_x emission from the spray combustion of kerosene has been studied in a large number of papers. Narato *et al.*²¹ recently reported NO_x emission of a premixing-prevaporizing flame of liquid fuels. In this study, the behavior of NO_x emission in the presently proposed burner is measured. Figure 9 shows the effect of the kerosene input load on the profiles of total NO_x , NO and NO_2 emissions for an equivalence ratio of 0.9. The values of NO_x concentration are those in residual O_2 0% and dry base. Although significant NO_2 formation was observed in the beginning of the flame, the NO formation gradually

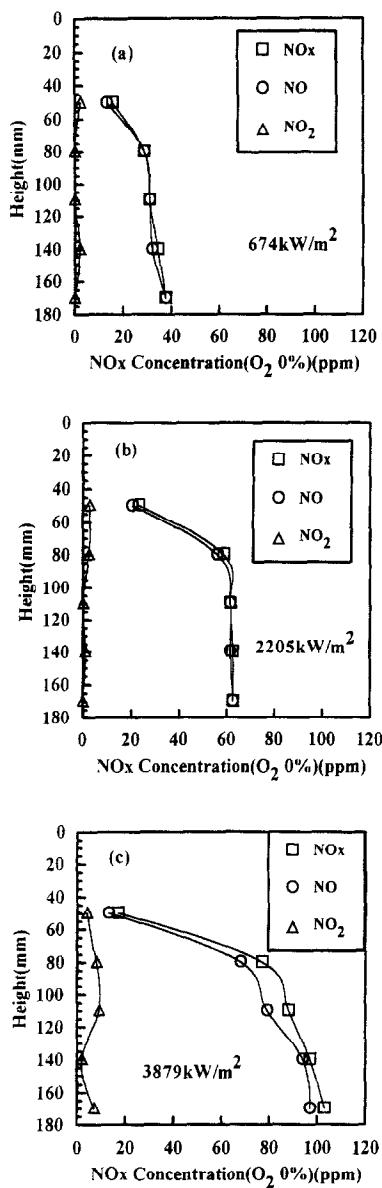


Figure 9 Effect of kerosene input on NO_x, NO and NO₂ concentration, $q = 0.9$

attained a dominant component in total NO_x towards the downstream flow. The NO_x emission was enlarged with an increase in the input load, and this trend is caused by the promotive effect of nitrogen oxidation due to a rise in the flame temperature. However, the maximum NO emission was less than 60 ppm for most runs except under extreme conditions. Figure 10 shows the effect of equivalence ratio on NO_x, NO and NO₂ emissions. The emissions at a height of 170 mm is barely influenced by the equivalence ratio. However, the configuration of the profiles is different depending on the oxygen concentration and the temperature in the flame zone.

Figure 11 shows the effect of the radiator on the profiles of total NO_x and NO emissions with a kerosene input of 1500 kW m⁻² in an equivalence ratio of 0.7. The NO_x emission rose significantly with the installation of the radiator. This high NO_x emission is explained by the difference of the temperature profiles, as described in the above section.

To evaluate NO_x emission behavior, the NO_x concentration measured at the height of 170 mm, (NO_x)_{exp}, is plotted in Figure 12 against the NO concentration, (NO)_{calc},

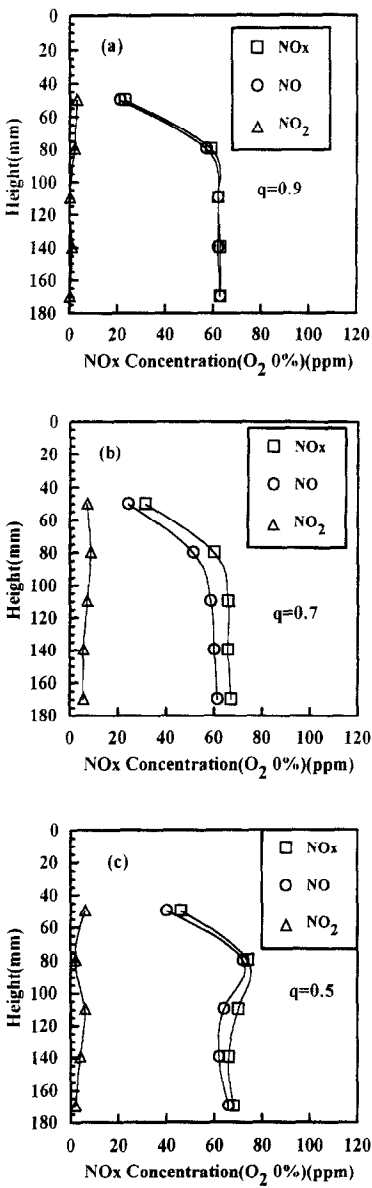


Figure 10 Effect of equivalence ratio on NO_x, NO and NO₂ concentration, kerosene input: 2205 kW m⁻²

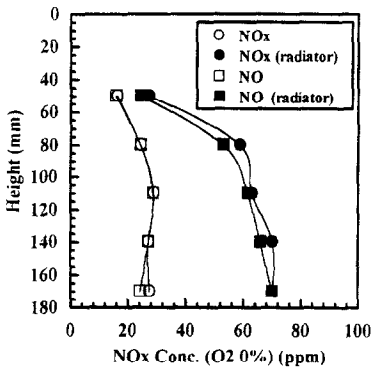


Figure 11 Effect of radiator on NO_x and NO concentration, kerosene input: 1500 kW m⁻²; $q = 0.7$

predicted from the Zeldovich mechanism that estimates the equilibrium concentration as follows:

$$[\text{NO}]^2 = [\text{N}_2][\text{O}_2](21.9) \exp(-1.82 \times 10^5/RT) \quad (1)$$

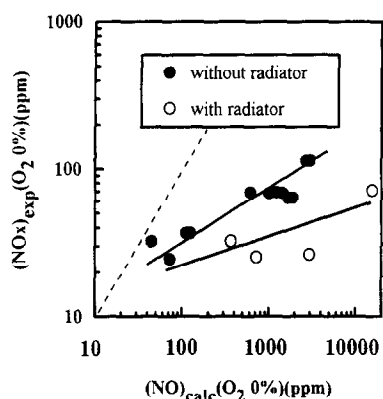


Figure 12 Effect of radiator on relation between $(\text{NO})_{\text{calc}}$ and $(\text{NO}_x)_{\text{exp}}$

The expression is applied to the maximum temperature in the flame since the reaction rate achieves a maximum there and is likely to dominate the NO_x formation through the reacting gas stream in the chamber. The composition measured at the height of 170 mm is adopted for the concentrations of oxygen and nitrogen in eqn (1). The NO_x formation reactions proceed gradually toward an equilibrium state corresponding to the composition after the completion of combustion or at the furnace exit. This is the reason why the NO_x emission is compared with the experimental data and the equilibrium concentration predicted from the composition in the downstream using the maximum temperature. Figure 12 shows the correlation between $(\text{NO}_x)_{\text{exp}}$ and $(\text{NO})_{\text{calc}}$ for a several equivalence ratio and load. The NO_x concentration measured in any run maintaining a stable flame is expressed approximately by a function of $(\text{NO})_{\text{calc}}$ for the present burner. The result proposes an empirical method that easily predicts NO_x emission after combustion is completed from the equilibrium concentration, although the correlation is limited to the present burner. The broken line denoting the function of $(\text{NO}_x)_{\text{exp}} = (\text{NO})_{\text{calc}} \cdot (\text{NO}_x)_{\text{exp}}$ shows remarkably smaller concentration than $(\text{NO})_{\text{calc}}$. This is because the prompt NO_x mechanism is not taken account in this calculation and $(\text{NO}_x)_{\text{exp}}$ does not achieve the equilibrium concentration that is predicted from the Zeldovich mechanism in the actual combustion field. The contribution of prompt NO_x is well known to be of importance for thermal NO_x formation. However, the mechanism is complex in order to take account of the prompt NO_x formation depending on the aerodynamics of gas streams, the heat transfer as well as the reaction kinetics. The low NO_x emission of this burner can be understood by a functional mechanism predicted from the composition profiles as follows. A fuel-rich flame is formed in the vicinity of the ceramic surface and then the combustion of the unburnt gas finally terminates in the downstream, i.e. the two-stage combustion may take place naturally in the flame. It is also noticed in the figure that the NO_x emission in the combustion with the installation of radiator is reduced compared with no installation of the radiator. As described in the previous section, NO_x concentration grew through the installation of the radiator due to the rise in temperature, but the behavior of NO_x emission is rather restrained if the evaluation is carried by the ratio to the equilibrium concentration in the combustion field, that is, it means that the increment of the NO_x concentration by the change of the boundary at the chamber outlet is less than that corresponding to the temperature rise. Although the

reason is not clear, the difference of the aerodynamic characteristic and the temperature field may favorably influence NO_x reduction.

CONCLUSION

The ceramic burner with a large turn-down ratio was developed for liquid fuels. The combustion characteristics of kerosene were investigated experimentally. The following results were obtained:

- (1) The fuel-lean limit of the kerosene–air flame attained a lean equivalence ratio of about 0.1.
- (2) The profiles of temperature and composition in the gas stream indicated that the flame length extended or the location shifted downstream with an increase in the input load or lean equivalence ratio.
- (3) The complete combustion of kerosene was observed in the input load range from 538 to 3879 kW m^{-2} . This corresponded to the turn-down ratio above 7.2.
- (4) The NO_x emission behavior was given successively by a function of the NO concentration in the equilibrium state predicted from a maximum temperature in the burner.
- (5) The combustion promotion effect was examined experimentally by installing the radiator at the chamber outlet.

REFERENCES

- 1 Mizutani, Y. and Nakajima, A., *Combustion and Flame*, 1973, **21**, 343.
- 2 Mizutani, Y. and Nakajima, A., *Combustion and Flame*, 1973, **20**, 351.
- 3 Williams, A., *Combustion and Flame*, 1973, **21**, 1.
- 4 Polymeropoulos, C. E. and Das, S., *Combustion and Flame*, 1975, **25**, 247.
- 5 Khalil, E. E. and Whitelaw, J. H., in *Sixteenth Symposium (International) on Combustion*. The Combustion Institute, Pittsburgh, PA, 1977, p. 569.
- 6 Mizutani, Y., Yasuma G. and Katsuki M., in *Sixteenth Symposium (International) on Combustion*. The Combustion Institute, Pittsburgh, PA, 1977, p. 631.
- 7 Chan, K. K. and Jou, C. S., *Fuel*, 1988, **67**, 1223.
- 8 Aly, S. L. and Salem, H., *Fuel*, 1989, **68**, 1203.
- 9 Tuttle, J.H., Colket, M.B., Bilger, R.W. and Mellor, A.M. in *Sixteenth Symposium (International) on Combustion*. The Combustion Institute, Pittsburgh, PA, 1977, p. 209.
- 10 Nizami, A.A. and Cernansky, N.P. in *Seventeenth Symposium (International) on Combustion*. The Combustion Institute, Pittsburgh, PA, 1979, p. 475.
- 11 Najjar, Y. S. H. and Goodger, E. M., *Fuel*, 1981, **60**, 980.
- 12 Isoda, T. and Azuma, T., *Transaction of JSME, Series B*, 1994, **60**(569), 314.
- 13 Meier, J. G. and Vollerin, B. L. in *Sixteenth Symposium (International) on Combustion*. The Combustion Institute, Pittsburgh, PA, 1977, p. 63.
- 14 Onuma, Y., Ogasawara, M. and Inoue, T., in *Sixteenth Symposium (International) on Combustion*. The Combustion Institute, Pittsburgh, PA, 1977, p. 561.
- 15 Owen, F. K., Spadaccini, L. J., Kennedy, J. B. and Bowman, C. T. in *Seventeenth Symposium (International) on Combustion*. The Combustion Institute, Pittsburgh, PA, 1979, p. 467.
- 16 Itaya, Y., Miyoshi, K., Maeda, S. and Hasatani, M., *International Chemical Engineering*, 1992, **32**(1), 123.
- 17 Nakamura, Y., Itaya, Y., Miyoshi, K. and Hasatani, M., *Journal of Chemical Engineering of Japan*, 1993, **26**(2), 205.
- 18 Itaya, Y., Jinno, K. and Hasatani, M., *Kagaku Kogaku*

Ronbunshu (Journal of Chemical Engineering of Japan), 1994, **20**(2), 301.

- 19 Hanamura, K., Saiki, N., Hayashi, T. and Echigo, R., *Transaction of JSME, Series B*, 1993, **59**(562), 2065.
- 20 Zhang, X. L., Vantelon, J. P. and Joulain, P., *Combustion and Flame*, 1993, **92**, 71.
- 21 Narato, K., Kobayashi, H., Murakami, T., Azuhata, S. and Kirigami, S., *Transaction of JSME, Series B*, 1993, **59**(563), 2317

NOMENCLATURE

$[\text{N}_2]$	mole concentration of N_2
$[\text{NO}]$	mole concentration of NO
$(\text{NO})_{\text{calc}}$	NO concentration predicted from eqn (1)
$(\text{NO}_x)_{\text{exp}}$	NO_x concentration measured
$[\text{O}_2]$	mole concentration of O_2
q	equivalence ratio